LUNAR DRILLING

NLSI Forum, ARC

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Visit: www.HoneybeeRobotics.com

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Short History Lunar Drilling

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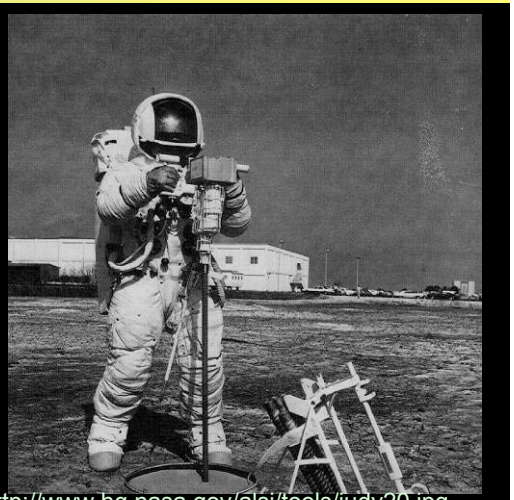
Apollo Lunar Surface Drill (1971, 1972)

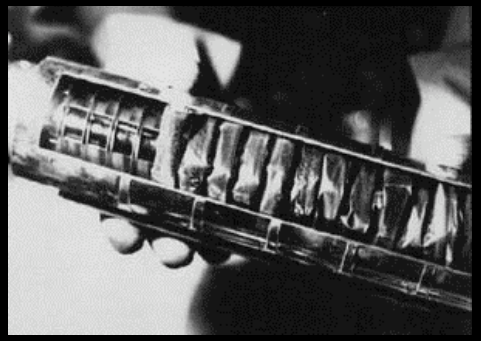
- ~500 Watt, Battery Powered (!!!) and Human Operated
- ~ 2.4 m depth
- A15: *The drill was hard to remove from the hole…it took both astronauts working at the limit of their combined strengths to pull up the drill …this caused a severe shoulder sprain in Scott.*
- 3rd Law of Robotics: *A robot must protect its own existence…*

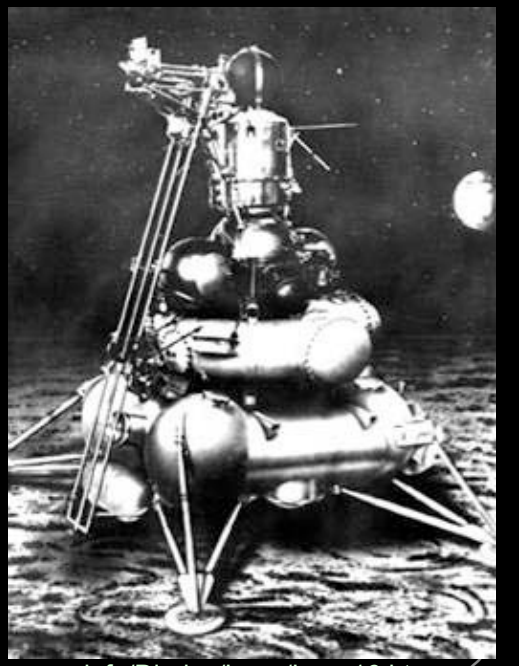


http://www.hq.nasa.gov/alsj/tools/judy20.jpg

Luna 16 (1970), 20 (1972), 24 (1976)

- Vacuum, +100 C to -170 C
- 1st Autonomous Drill
- 5727 kg Platforms
- Depths of 35 cm, 25cm, & 2 m





http://www.zarya.info/Diaries/Luna/Luna16.htm

"Lunar" Lessons Learned

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1. Drilling is not that simple
2. Drilling on another body is tough – even when humans are doing the job
3. Large spacecrafts or human operation are currently things of the past (at least for now)
4. AND….There is no substitute for testing…in relevant environment –

" test early and often"!

Subsurface exploration approaches

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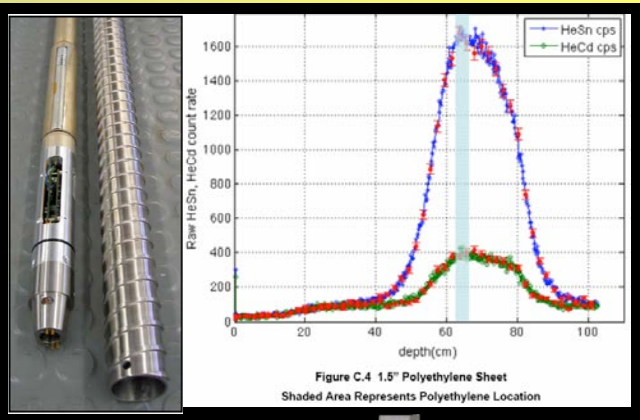
1. Bring Sensor downhole

   Example: NS/IR drill

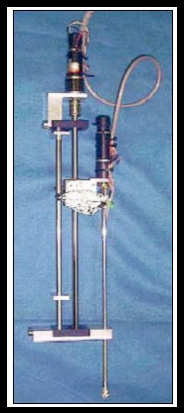
   - Non-contact or contact sensor inside a drill
   - NS- water wt%, IR-mineralogy



2. Bring Vapors to an Instrument

   Example: Sniffer

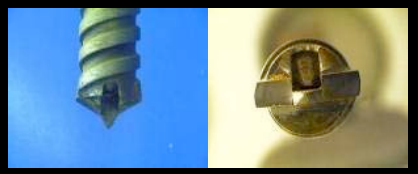
   - Captures cuttings in a drill tip
   - Sample heater, vapors travel to a MS



3. Bring Sample to an Instrument

   Example: Auger or Bit Sampler

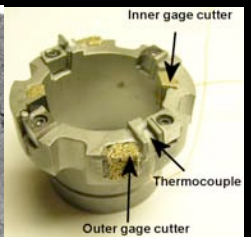
   - Acquires locally mixed powder sample
   - Bring samples on auger flutes



4. Bring a Core to an Instrument

   Example: Coring drill

   - Acquires core and brings it to a processing unit.



Mission Complexity vs. Payoff

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Complexity

Payoff

Downhole

Step 1: Drill

Step 2: Analyze

Sniffer

Step 1: Drill

Step 2: Acquire Sample

Step 3: Analyze

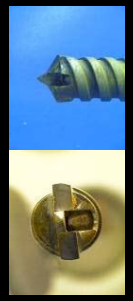
Sample

Step 1: Drill

Step 2: Pull Out

Step 3: Transfer Cuttings

Step 4: Analyze



Core

Step 1: Drill

Step 2: Break-off core

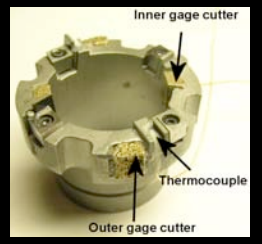
Step 3: Capture Core

Step 4: Pull out

Step 5: Eject core

Step 6: Process core

Step 7: Analyze



Honeybee Drills

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- Since 1990s we built and tested all four different drill types.
- We also built flight systems: MER RAT, Phoenix Scoop, Dust Removal Tool on MSL
- **What we learned: when developing a system, you need to outline a path to flight from start.**

Note: images not to scale

RAT Rock Abrasion Tool

TGSS Touch & Go Surface Sampler

Mini-Corer

GSFC Mole

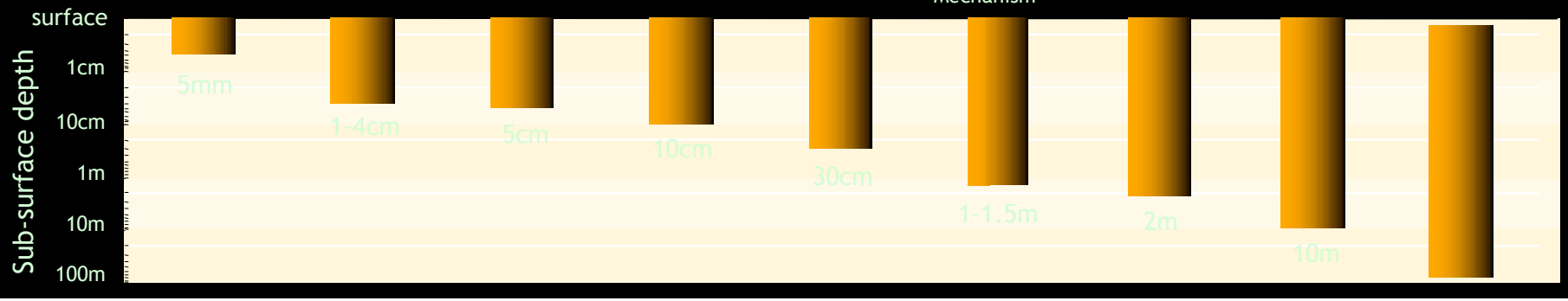
Sniffer Sampling and Gas Analyzer System

SATM Sample Acquisition & Transfer Mechanism

Telescoping Drill

Deep Drill

Inchworm Deep Subsurface Platform



Previous Honeybee 1m class Drills

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	Mars Deep Drill	MARTE	DAME	SATM
				
TRL	5/6	5/6	5	6
Sample Type	Cuttings	Core (1”x 10”)	Cuttings	0.1cc cuttings at the bit
Focus	Robotic drill string connections.	Robotic string connections, core break-off, capture and ejection.	Drilling Autonomy (Hands-off drilling, fault recognition and mediation etc).	Mass: 10kg. Stroke 1.2m. 25 Whr @ 1 cm/min in 40 MPa material
Instrumentations	Neutron and IR Spectrometer			Sample acquisition at the bit.
Testing	8.3m in Arizona	>8m California and Spain	>3m Arctic (2004-2007)	Lab
Location	At LANL	At ARC	At ARC	At JPL

Lessons learned

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1. **Lessons are expensive**

2. **Drills are too complex**
- **Honeybee Solution**: Down hole instrumentations

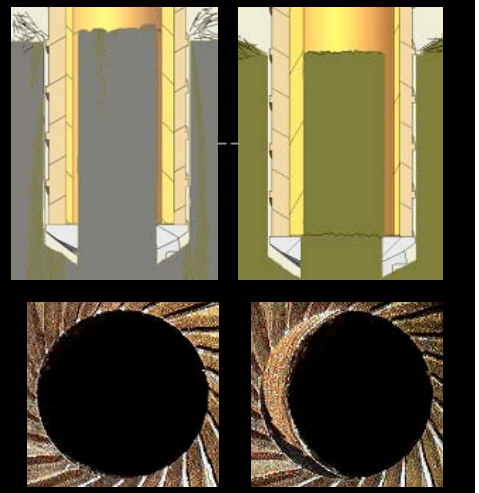
3. **Core handling is a big issue**
- Problems:
  - Breaking a core in all formations: Soil, Icy-soil, Ice, Rock
  - Retaining a core: Not many systems have 100% core recovery!
  - Ejecting a core: Can't rely on gravity/vibration, core could freeze
  - Ok, so you have a core and now what? Crush it? Slice it?
- **Honeybee Solution**: Capture cuttings using sampling auger

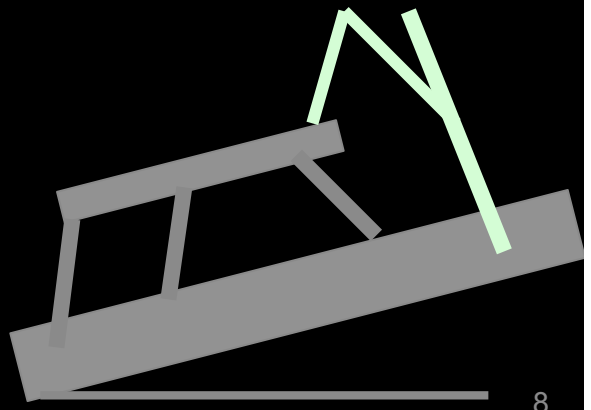
4. **Drills required too much Weight on Bit**
- Problems:
  - Had to assume boom deployable system
  - Maximum WOB <100N
- **Honeybee Solution**
  - Rotary-Percussive or Sonic systems (vacuum rated)

Patented

Drilled to Depth

Shear & Capture Core





Recap:

1. Downhole instruments
2. Auger Sampling
3. Percussive or Sonic drilling

Downhole Neutron Spectrometer and IR

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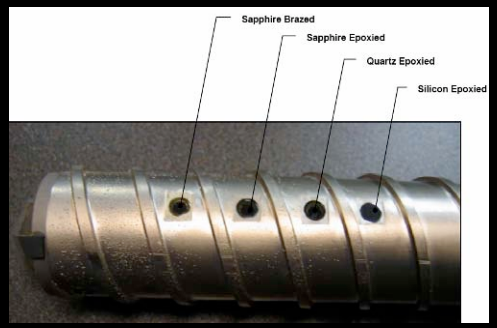
Neutron Spectrometer

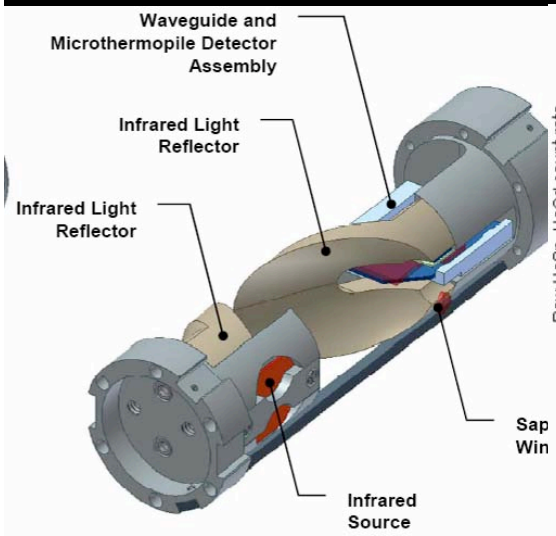
- Used to ground truth areas identified by surface NS as H_2 rich
- Dual sensors and electronics: 0.5kg and 2.2W (R. Elphic)
- Possibility for borehole sampler
- TRL 5/6

Infra Red Spectrometer

- Mineralogy
- Emissivity, thermal inertia
- TRL 3



R. Elphic NS on ARC K10 mini



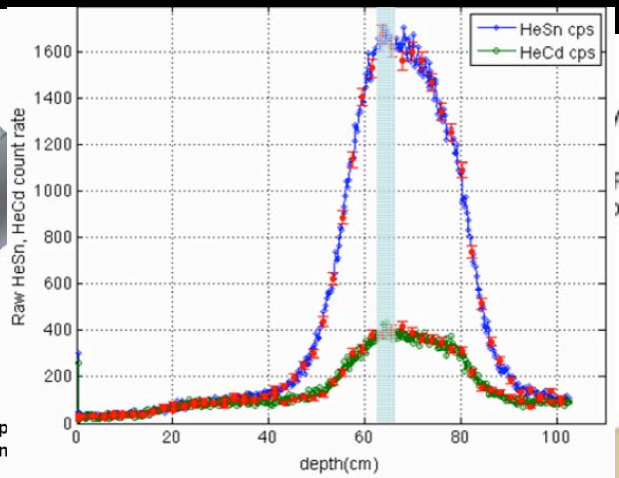
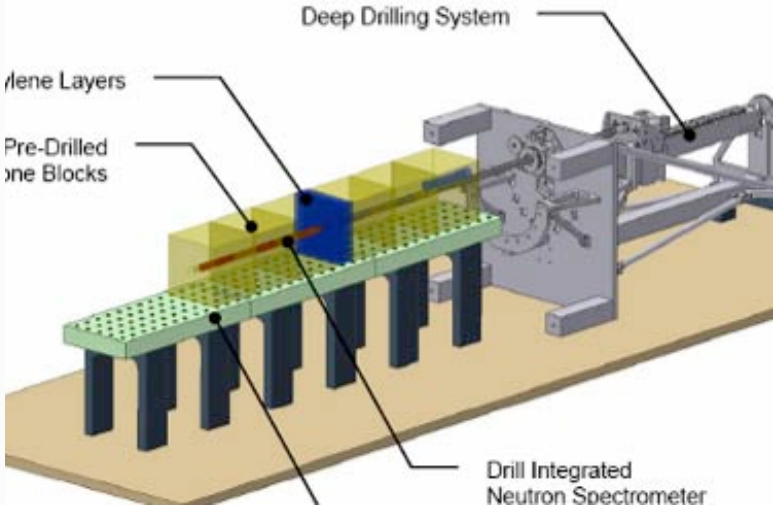


Figure C.4 1.5" Polyethylene Sheet
Shaded Area Represents Polyethylene Location



Drill With a Laser Induced Breakdown Spectroscopy

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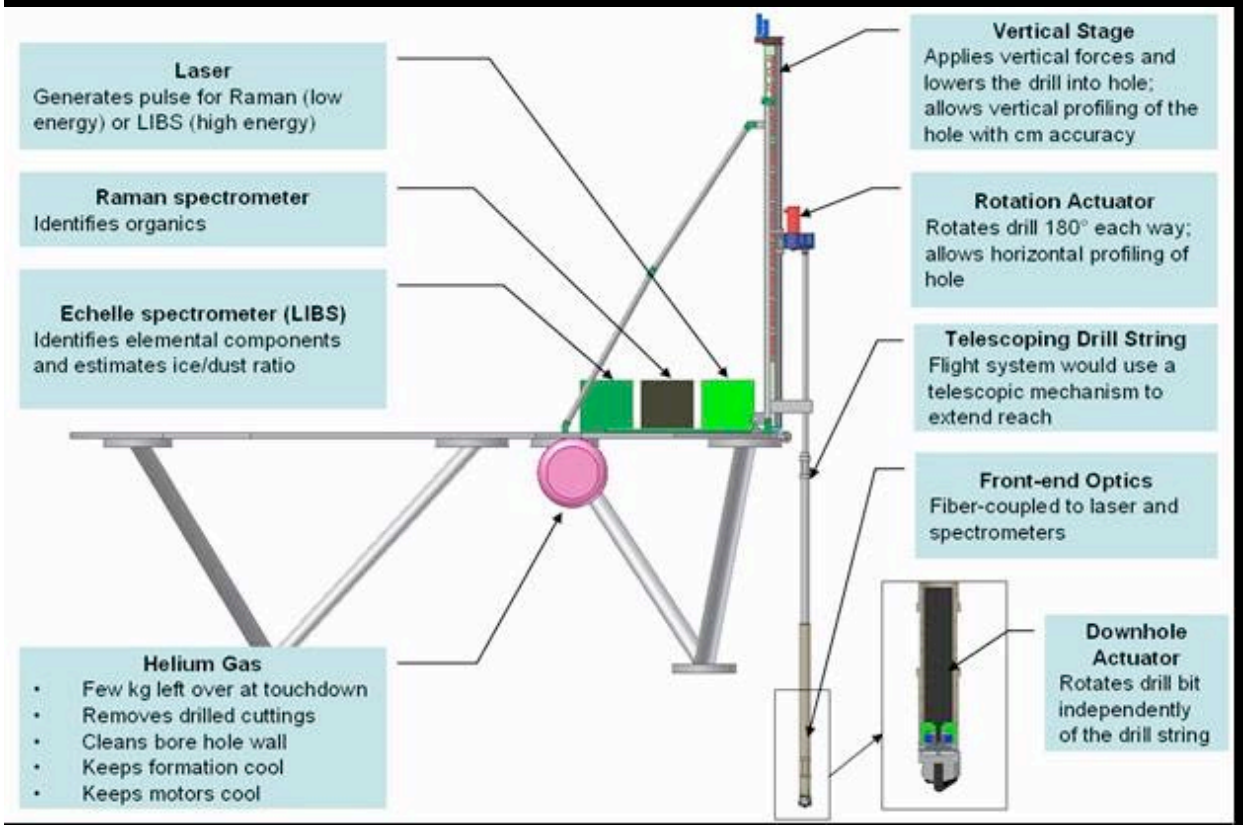
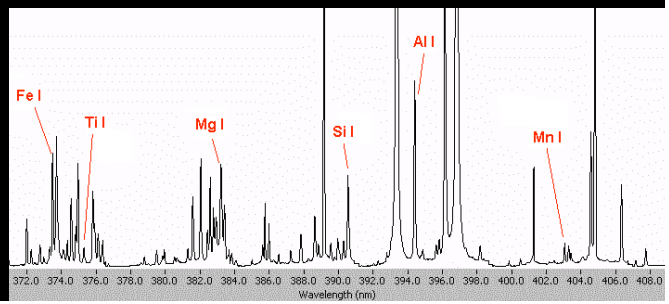
- In situ, 3D subsurface elemental composition
- Extremely robust. LIBS developed for mining customers (heat, vibration, dust).
- TRL5 system is being designed (SBIR-MSFC)
  - Telescopic design allows deep penetration without extra mass
  - Pressurant Helium used for removing cuttings (reduces drilling power, energy, heat)



Accuracy: NU-LHT-2M

	Actual wt%	LIBS wt%	Deviation (% relative)
Fe_2O_3	4.16	3.61	-13%
TiO_2	0.41	0.47	+14%

LIBS Spectra: JSC-1a



Current Sampling Drill Developments

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	Sonic	CRUX	IceBreaker
			
TRL	5	5	5 (6 in 07/2010)
Sample Type	Cuttings	Cuttings	Cuttings
Focus	Vacuum rated Sonic drilling technology. Gas assisted drilling. Bit Preload <100N	Percussive drilling technology Bit Preload <100N	Vacuum rated percussive drilling technology Bit Preload <100N
Instrumentations	Bit Temperature	Bit Temperature Downhole Camera	Bit Temperature Downhole Camera
Testing	1m in Vacuum Chamber	>2m Arctic (2009, 2010)	1m in Vacuum Chamber Antarctic, 2010
Location	At Honeybee	At ARC	At Honeybee

Auger Sampler: How it Works

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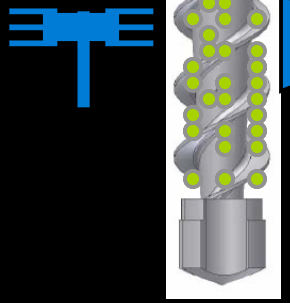
Tapered auger. Deep flutes at the bottom – shallow flutes on top.

Drill 1st 2in bite

Pull out. Image cuttings laying on auger flutes, sub sample.

Scraper/Brush

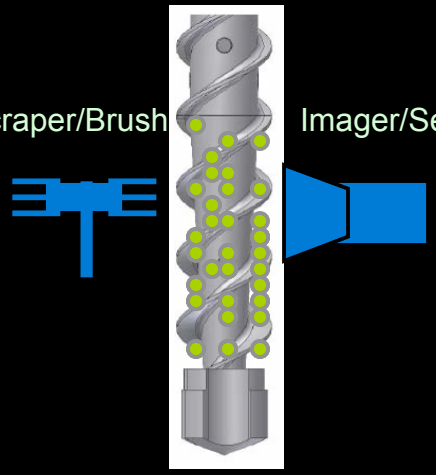


Imager/Sensor

Drill 2nd 2in bite

Pull out. Image cuttings laying on auger flutes, sub sample.

Scraper/Brush



Imager/Sensor

Drill 3rd 2in bite

Heat Pipe moves excess heat from the bit to the lander

Auger Sampler

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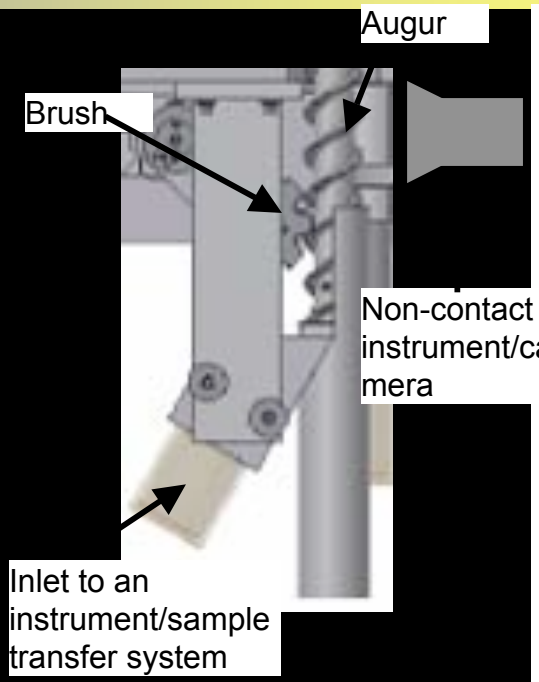
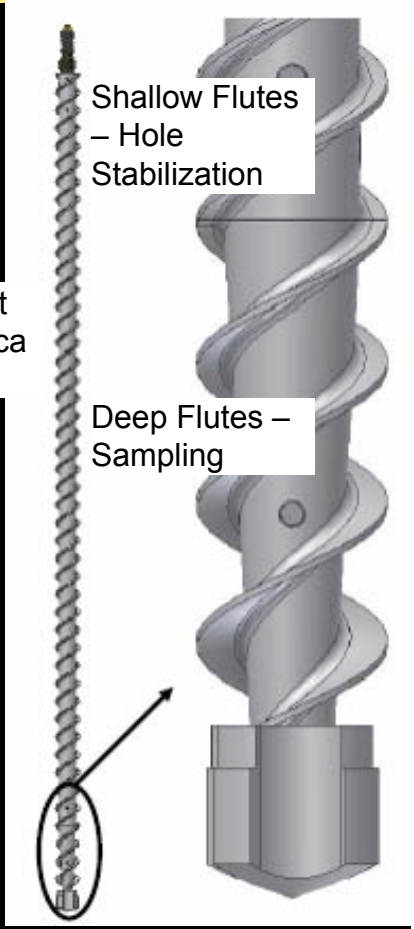
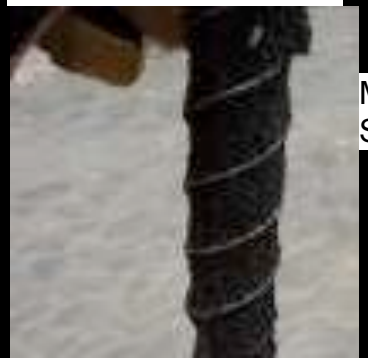
- Very simple operation:
  - Drill short bites e.g. 4 inches
  - If drill gets stuck at 20in, you still have 5 samples!
- Cuttings can be imaged and analyzed with non-contact instruments while on auger flutes
- Only cuttings of interest can be moved into an instrument and analyzed, the rest can be discarded (brushed off)
- Stratigraphy is preserved – cuttings on top come from top part of the hole
- Very robust system:
  - If cuttings get stuck on flutes, they can be brushed off
- System under development for Mars IceBreaker 1-2m drill mission will be tested in Antarctic in Dec 2010.





Cuttings on auger flutes during Mauna Kea tests



Manual Sub-Sampling

Test Early and Often

Testing in relevant environment!

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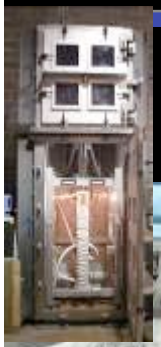

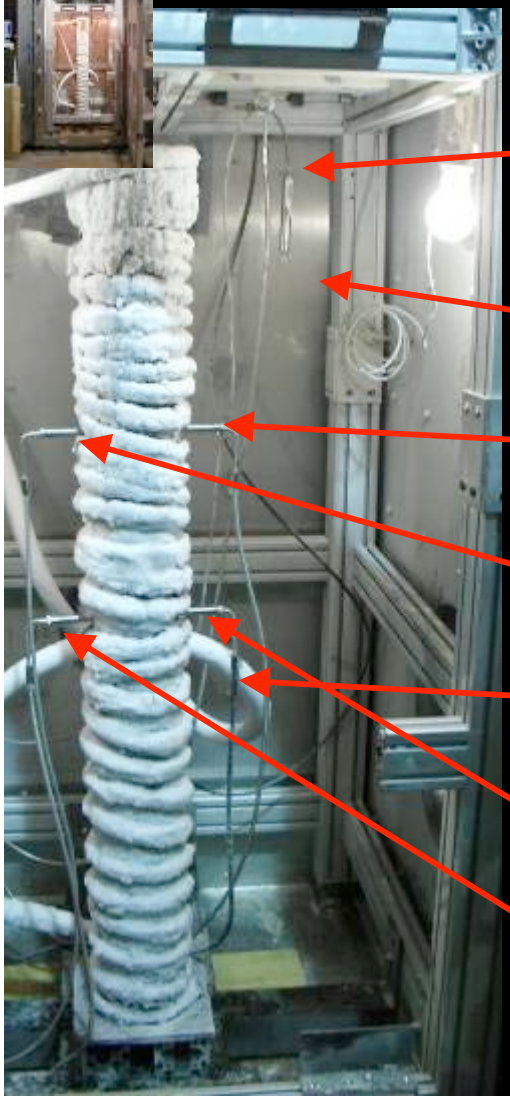

Ambient Temp.

Relative Humidity

Temp. 2
(14” from top, 1” deep)

Temp. 3
(14” from top, 0.5” deep)

Chamber Pressur

Temp. 4
(24” from top, 1” deep)

Temp. 5
(24” from top, 0.5” deep)

>70 permutations

No°	P, torr	Sample	Sample	WOB, N	RPM	Gas?	RP/RS/R
1	760	Indiana LS	Room T	<100	100	N	R
2	760	Indiana LS	Room T	<100	100	N	RP
3	760	Indiana LS	Room T	<100	100	N	RS
4	760-3	Indiana LS	Room T	<100	100	N	R
5	760-3	Indiana LS	Room T	<100	100	N	RP
6	760-3	Indiana LS	Room T	<100	100	N	RS
7	760-3	Indiana LS	Room T	<100	100	N	R
8	760-3	Indiana LS	Room T	<100	100	N	RP
9	760-3	Indiana LS	Room T	<100	100	N	RS
10	6.4	Indiana LS	Room T	<100	100	N	R
11	3	Indiana LS	Room T	<100	100	N	R
12	6.4	Indiana LS	Room T	<100	100	N	RP
13	3	Indiana LS	Room T	<100	100	N	RP
14	6.4	Indiana LS	Room T	<100	100	N	RS
15	3	Indiana LS	Room T	<100	100	N	RS
16	6.4	Ice	-20	<100	100	N	R
17	3	Ice	-20	<100	100	N	R
18	6.4	Ice	-20	<100	100	N	RP
19	3	Ice	-20	<100	100	N	RP
20	6.4	Ice	-20	<100	100	N	RS
21	3	Ice	-20	<100	100	N	RS
22	6.4	Ice + 2% Phr	-20	<100	100	N	R
23	3	Ice + 2% Phr	-20	<100	100	N	R
24	6.4	Ice + 2% Phr	-20	<100	100	N	RP
25	3	Ice + 2% Phr	-20	<100	100	N	RP
26	6.4	Ice + 2% Phr	-20	<100	100	N	RS
27	3	Ice + 2% Phr	-20	<100	100	N	RS
28	3	JSC-1a+12wt%	-20	<100	100	N	R
29	6.4	JSC-1a+12wt%	-20	<100	100	N	R
30	3	JSC-1a+12wt%	-20	<100	100	N	RP
31	6.4	JSC-1a+12wt%	-20	<100	100	N	RP
32	3	JSC-1a+12wt%	-20	<100	100	N	RS
33	6.4	JSC-1a+12wt%	-20	<100	100	N	RS
No°	P, torr	Sample	Sample	WOB, N	RPM	Gas?	RP/RS/R
34	3	JSC-1a+12wt%	-40	<100	100	N	R
35	3	JSC-1a+12wt%	-200	<100	100	N	R
36	3	JSC-1a+12wt%	-40	<100	100	N	RP
37	3	JSC-1a+12wt%	-200	<100	100	N	RP
38	3	JSC-1a+12wt%	-40	<100	100	N	RS
39	3	JSC-1a+12wt%	-200	<100	100	N	RS
40	6.4	Sat. DI Breccia	-20	<100	100	N	R
41	6.4	Sat. DI Breccia	-20	<100	100	N	RP
42	6.4	Sat. DI Breccia	-20	<100	100	N	RS
43	6.4	MMS saturated	-20	<100	100	N	R
44	6.4	MMS saturated	-20	<100	100	N	RP
45	6.4	MMS saturated	-20	<100	100	N	RS
46	760	Saddleback B	20	<100	100	N	R
47	760	Berea SS	20	<100	100	N	R
48	760	Indiana LS	20	<100	100	N	R
49	760	Saddleback B	20	<100	100	N	RP
50	760	Berea SS	20	<100	100	N	RP
51	760	Indiana LS	20	<100	100	N	RP
52	760	Saddleback B	20	<100	100	N	RS
53	760	Berea SS	20	<100	100	N	RS
54	760	Indiana LS	20	<100	100	N	RS
55	6.4	Ice	20	<100	100	G	R
56	6.4	JSC-1a+12wt%	20	<100	100	G	R
57	6.4	Berea SS	20	<100	100	G	R
58	6.4	Ice	20	<100	100	G	RS
59	6.4	JSC-1a+12wt%	20	<100	100	G	RS
60	6.4	Berea SS	20	<100	100	G	RS
61	760	Berea SS	20	<100	60	N	R
62	760	Berea SS	20	<100	100	N	R
63	760	Berea SS	20	<100	120	N	R
64	760	Berea SS	20	<100	60	N	RP
65	760	Berea SS	20	<100	100	N	RP
66	760	Berea SS	20	<100	120	N	RP
67	760	Berea SS	20	<100	60	N	RS
68	760	Berea SS	20	<100	100	N	RS
69	760	Berea SS	20	<100	120	N	RS
70	760	Antarctic soil	-20	<100	100	N	RP
71	6.4	Antarctic soil	-20	<100	100	N	RP
72	760	PP	20	<100	100	N	R
73	760	PP	20	<100	100	N	RP
74	760	PP	20	<100	100	N	RS

Drilling in vacuum in Ice

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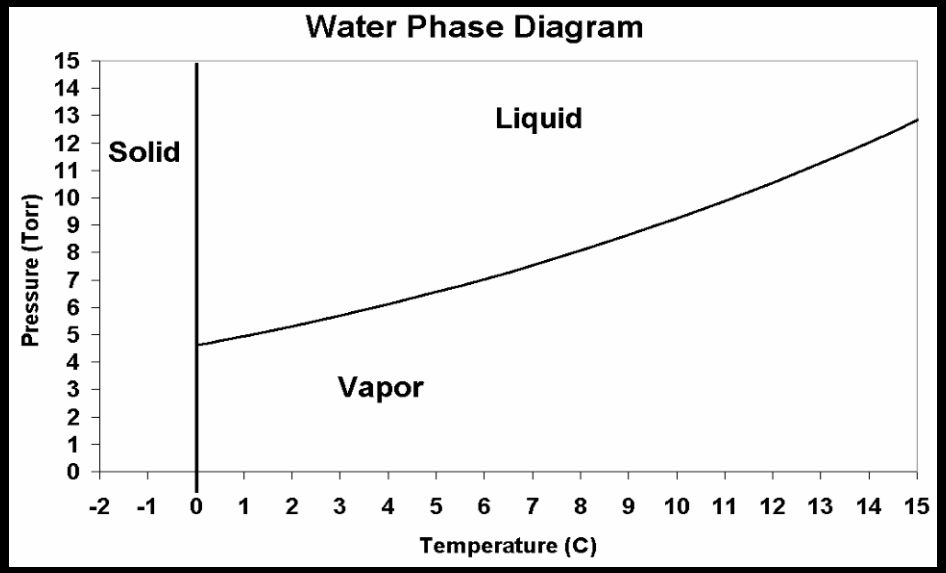
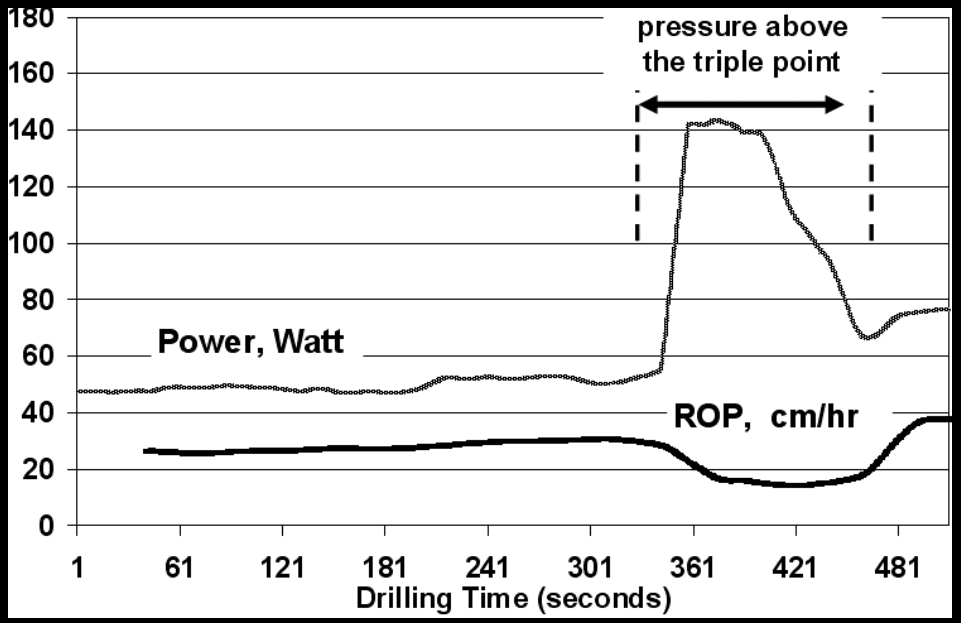


- Drilling power --> heat --> latent heat --> sublimation
- Volumetric expansion of water 150,000 times



References

HONEYBEE ROBOTICS
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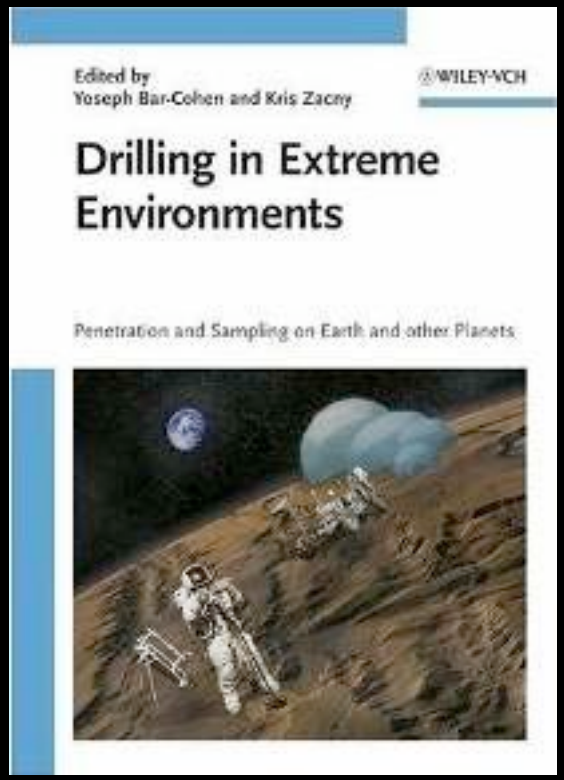
Y. Bar-Cohen and K. Zacny (Eds.),

"Drilling in Extreme Environments - Penetration and Sampling on Earth and Other Planets,"

- Chapter 1: Introduction
- Chapter 2: Principles of Drilling and Excavation
- Chapter 3: Ground Drilling and Excavation
- Chapter 4: Ice Drilling and Coring
- Chapter 5: Sea Floor drilling
- **Chapter 6: Extraterrestrial Drilling and Excavation**
  - **Over 50 scoops, drills, penetrometers, moles etc.**
- **Chapter 7: Planetary sample acquisition, handling and processing**
- **Chapter 8: Instruments for In-Situ Sample Analysis**
- **Chapter 9: Contamination and Planetary protection**



Zacny et al., **Drilling Systems for Extraterrestrial Subsurface Exploration**, ASTROBIOLOGY Volume 8, Number 3, 2008 (42 pages)

>30 other extraterrestrial drilling papers

Acknowledgements

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NOW YOU CAN "DRILL" ME WITH QUESTIONS

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